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# Monolithic integration of collimating Fresnel lens for beam quality enhancement in tapered high power laser diode

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## ABSTRACT

We demonstrate, for the first time, a monolithic integrated lens for wide aperture gain-guided tapered laser beam quality enhancement by compensating the quadratic phase curvature. The 3mm long tapered laser with an output aperture of 170 $\mu$ m adopted in this design consists of a gain-guided tapered section and an index-guided ridge section and operated at 980nm. The lens design is implemented by focus ion beam etching (FIBE) technique, whereby the laser diode is mounted p-side up in order to facilitate the etching process. The lens is located 600 $\mu$ m away from the junction of the tapered and ridge sections, and is 40 $\mu$ m wide and 300 $\mu$ m long with a focal length of 800 $\mu$ m. The laser diode is characterised by light-current characteristics together with near- and far- field measurements before and after etching. The device is biased by current pulses of 1 $\mu$ s width and 0.1% duty cycle. Light-current measurement shows a drop of 10.5% in threshold current from 380mA to 340mA after the inclusion of lens. This is an evidence that the lens effectively equalised the curved phase in order to reduce the laser cavity loss by improving the coupling efficiency of backward travelling wave at the output facet. Throughout the whole current range tested, the width of near-field at waist is broadened by an average of 36% after the inclusion of lens. By successfully compensating the quadratic phase curvature of the mode, the beam divergence in the far-field is significantly narrowed by an average of 28.5%. M<sup>2</sup> factor is improved by an average of 12%.

**Keywords:** high power laser diode, high brightness laser diode, tapered laser structure, beam quality, integrated Fresnel lens, semiconductor laser, gain guiding, 980nm.

## 1. INTRODUCTION

High-power coherent optical beams are needed for a number of applications in the fields of fibre and space telecommunication [1], medicine [2] and manufacturing [3]. High-power semiconductor lasers offer the advantage of small size, high efficiency, improved reliability and reduced cost compared with solid-state and gas lasers. While high optical power can be achieved easily by increasing the active volume in broad area lasers, brightness will be seriously degraded from filamentation which leads to poor beam properties in the far-field [4]. A number of structures have been proposed, such as, for example, unstable resonator lasers [5], master oscillator power amplifier (MOPA) lasers [6],  $\alpha$  – grating distributed feedback lasers [7], external cavity grating-tuned lasers [8] and tapered lasers [9]. Tapered lasers have received the greatest attention due to the technological simplicity of their fabrication.

The fibre coupling efficiency of a laser diode relies upon small beam divergence angle, and this has led to research in the design of integration of lens with laser diode. Traditional lens designs are based on focusing plane wave into a small spot [10-11]. In contrast, the design presented in this paper is to equalise the curved wavefront within the laser cavity with Fresnel lens, thereby making the output wave of the laser as close to plane wave as possible in order to reduce the raw far-field divergence angle (see Figure 1a). Earlier work had shown the feasibility of improving the beam quality of an index-guided device with a 30 $\mu$ m wide output aperture [12]. However the capability of such configuration is greatly limited by the device output aperture size making it impossible to be realised in large tapered device. The work presented in this paper is designed to eliminate this limitation. In order to demonstrate this superiority, a large output aperture gain-guide tapered laser with a 170 $\mu$ m wide output aperture is adopted for our work.

## 2. DEVICE STRUCTURE

Figure 1a shows a schematic diagram of a parabolic lens integrated with a tapered laser. The 3mm long tapered laser adopted in this design consists of a gain-guided tapered section and an index-guided ridge section and operated at 980nm [9]. The front facet and back facet are coated with anti-reflection (AR) coating and high-reflection (HR) coating respectively. The lens design is implemented by focus ion beam etching (FIBE) technique, whereby the laser diode is mounted p-side up in order to facilitate the etching process. The lens is located 600 $\mu\text{m}$  away from the junction of the tapered and ridge sections, and is 40 $\mu\text{m}$  wide and 300 $\mu\text{m}$  long with an etch depth of 1.6 $\mu\text{m}$ . The scanning ion microscope image of the lens is shown in Figure 1b.

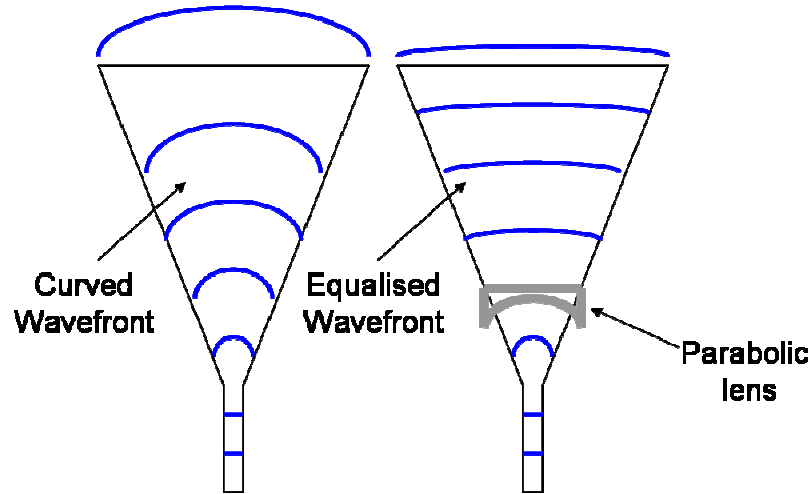


Figure 1a: Schematic of parabolic lens design,

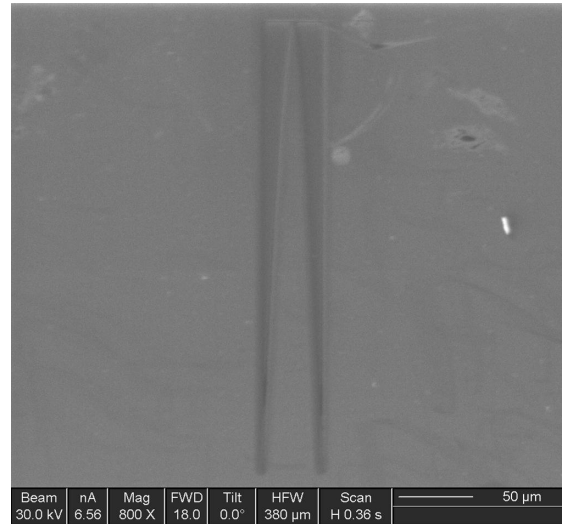


Figure 1b: Scanning ion microscope image of the etched lens

### 3. DEVICE CHARACTERISATION

#### 3.1 Experimental setups

The laser diode is characterised by light-current characteristics together with near- and far- field measurements before and after etching. The device is biased by current pulses of  $1\mu\text{s}$  width and 0.1% duty cycle. The near-field measurements are carried out using a charge coupled device (CCD) camera placed in a distance of 40cm away from the laser output facet and a microscope objective lens for focusing. The near-field image is then processed by a beam analysis software. The far-field measurements are performed by rotating a photodiode located at 30cm in front of the laser output facet, and is shown in Figure 2. A slit is placed in front of the photodiode to ensure a measurement resolution of  $<0.1^\circ$ .

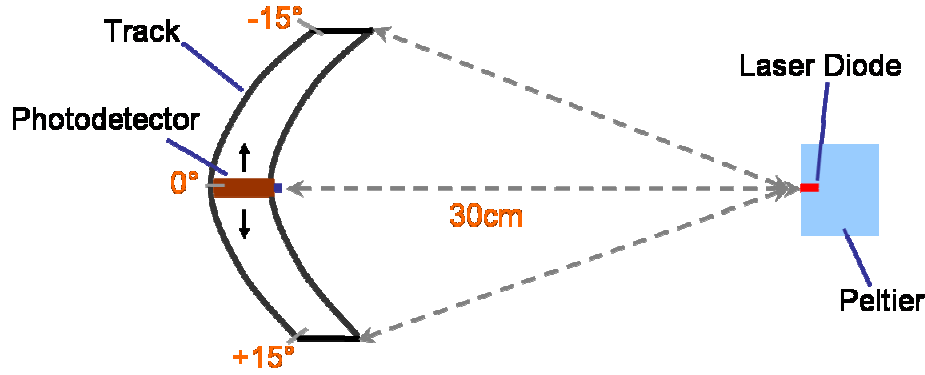


Figure 2: Far-field measurement setup

#### 3.2 Experimental results

Light-current measurement shows a drop of 10.5% in threshold current from 380mA to 340mA after the inclusion of lens. This is an evidence that the lens effectively equalised the curved phase in order to reduce the laser cavity loss by improving the coupling efficiency of backward travelling wave at the output facet.

Due to the gain-guided nature of the optical field within the tapered section of the laser cavity, a large degree of astigmatism is present. The beam waist of the lateral field is some distance away from the facet inside the laser cavity, and is highly sensitive against injection current. Figure 3 shows the schematic of it.

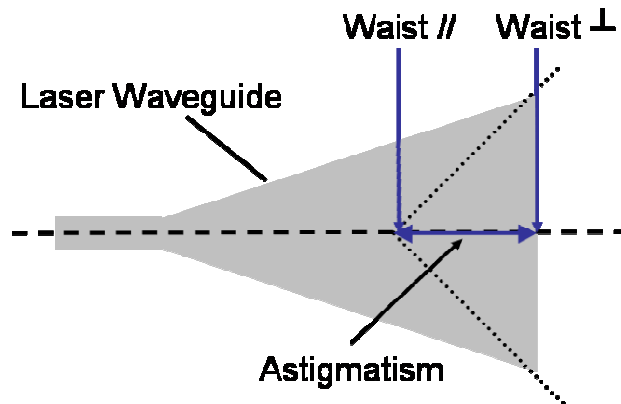


Figure3: Schematic of the astigmatism in gain-guided tapered laser

The lateral near-field at waist is measured and its widths at  $1/e^2$  are plotted against the normalised currents with and without lens as shown in Figure 4. The current is normalised with respect to the laser threshold current. The widths at every normalised current step are broadened by an average of 36%.

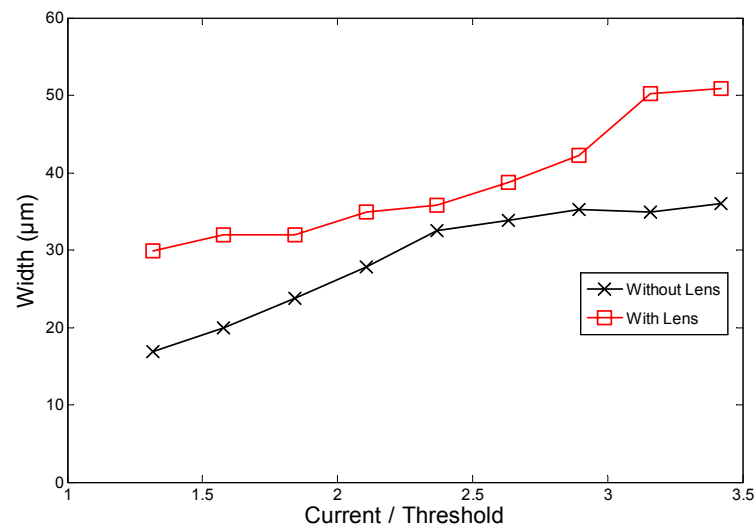


Figure 4: Near-field at waist width at  $1/e^2$  intensity against normalised current with and without

The lateral near-field at facet is also measured; results are shown in Figure 5. The widths at every normalised current step are reduced by an average of 24%.

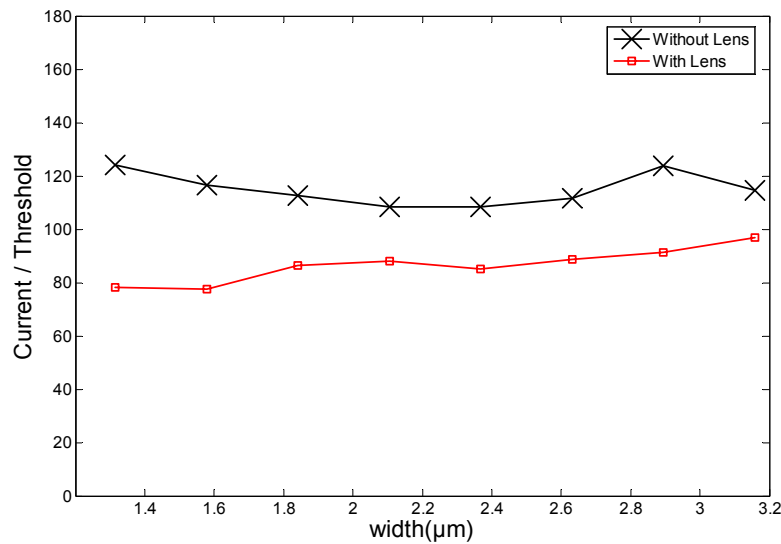


Figure 5: Near-field at facet width at  $1/e^2$  intensity against normalised current with and without lens

By successfully compensating the quadratic phase curvature of the mode, the beam divergences in the far-field at every normalised current level are significantly narrowed by an average of 28.5% (see Figure 6).

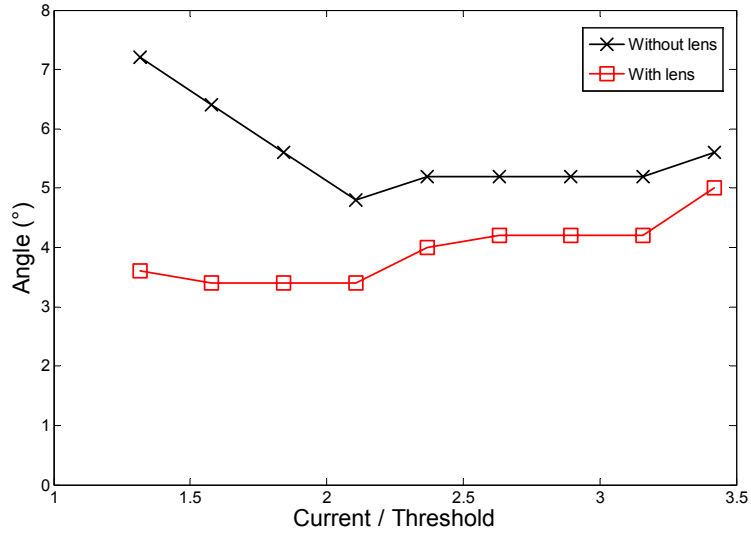


Figure 6: Far-field divergence angle at  $1/e^2$  intensity against normalised current with and without

An example of the far-field profiles at 1.32 times threshold current is shown in Figure 7. It is also observed that the fluctuation of astigmatism with biased current is highly stabilised. This enhances its ability in fibre coupling.

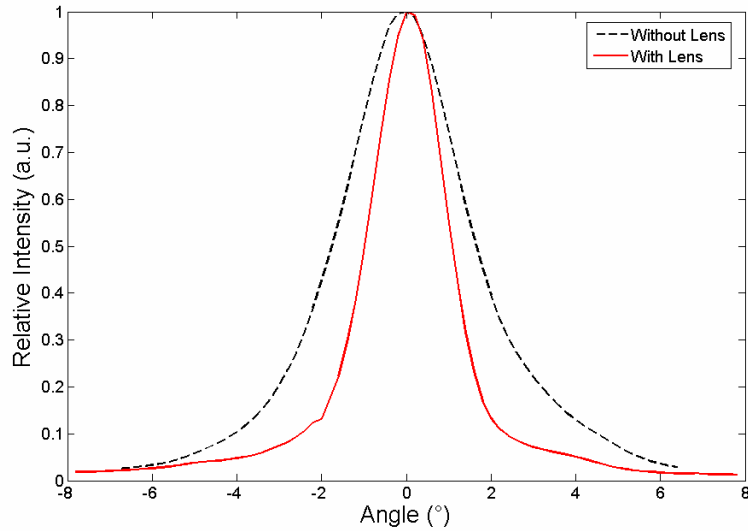


Figure 7: Far-field profile at 1.32 times threshold current

Figure 8 shows the far-field profiles of the laser diode with and without the integration of lens. It is observed that the variations of the far-field profiles are significantly reduced. This will again provide great advantage in its ability in fibre coupling.

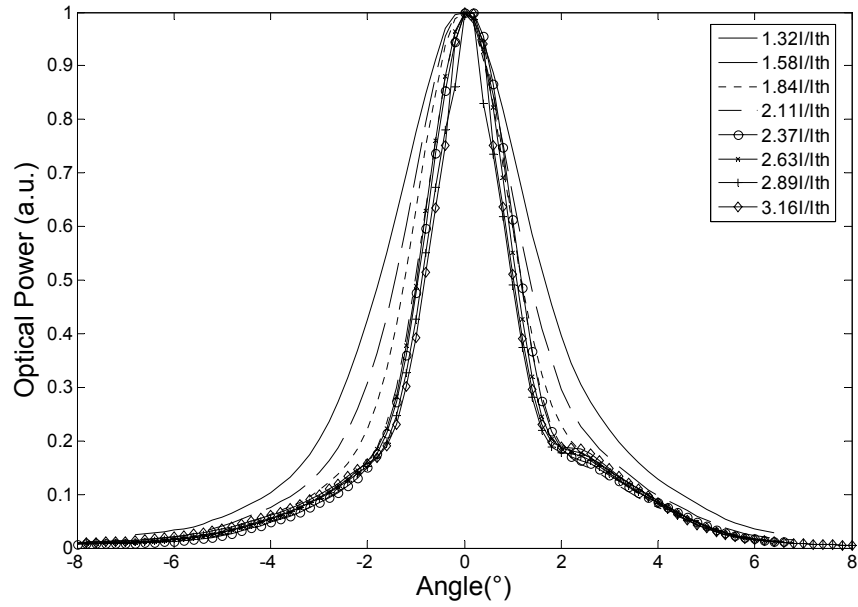


Figure 8a: Far-field profile at different injection currents without the integration of lens

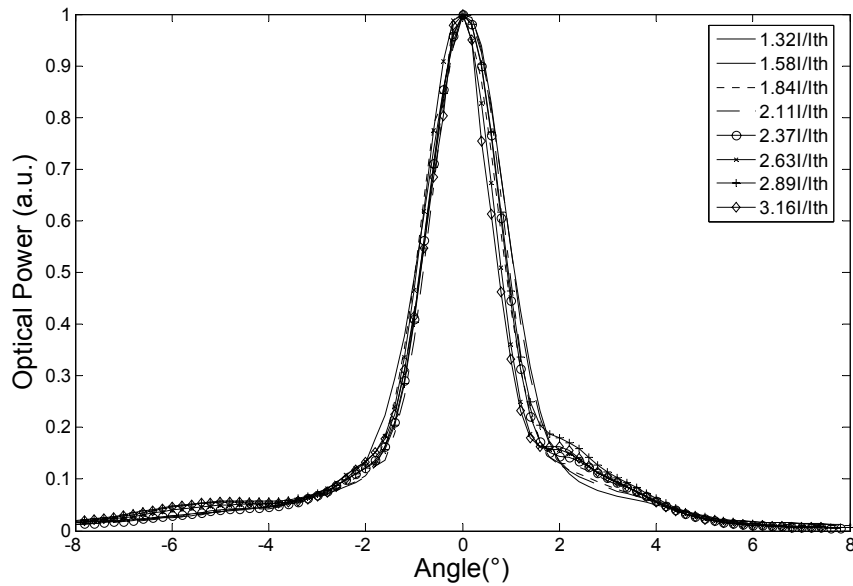


Figure 8b: Far-field profile at different injection currents with the integration of lens



The  $M^2$ -factor of the laser is calculated based on the emission wavelength, the divergence angle of the experimental far-field at  $1/e^2$  and the width of the experimental near-field at waist at  $1/e^2$  [13]. Figure 9 plots the calculated  $M^2$  values against the normalised current. The  $M^2$  factors are improved in an average of 12% until 2.9 times threshold. However the  $M^2$  values slightly increased slightly after this point due to the broadening of the near-field width at waist which in turn reduced the diffraction limit.

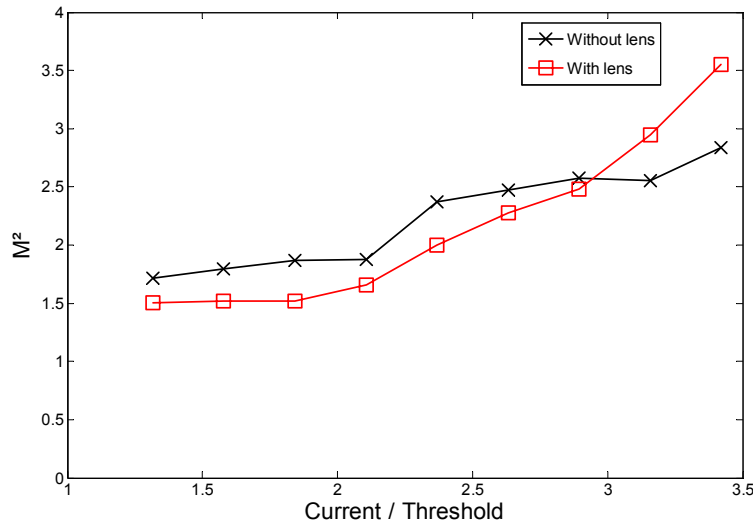


Figure 9:  $M^2$  values against normalised current with and without lens

#### 4. CONCLUSIONS

In summary, the applicability of laser beam quality enhancement by means of etching a monolithic integrated Fresnel lens in a gain-guided tapered laser diode is successfully demonstrated. This shows that the limitation of output aperture size appeared in previous design is completely eliminated. The functions of the lens shown by experimental results include threshold current drop of 10.5%, broadening of near-field with at waist by a mean value of 36%, 28.5% mean reduction in average far-field divergence angle, improvement on astigmatism stability against biased current and significant reduction in the variation of far-field profiles at different injection current.

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